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DISPERSION OF SUBSTANCES AND CALCULATION OF THE CRATER DEPTH IN HIGH-VELOCITY IMPACTS

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A hydrodynamic model of the process of dispersion of bodies in high-velocity impacts is considered. The depth of craters formed on impact of bodies against a semiinfinite surface is calculated. The possibility of applying the results obtained to the superdeep-penetration effect is discussed.

As is known, pressures from several hundred thousand to a million atmospheres develop in a shock wave for impact velocities of (1–10) km/sec. The unloading of bodies at such pressures is accompanied by the dispersion, melting, and partial evaporation of the materials of the striker and the target. Thus, the estimative values of the pressure in a shock wave obtained experimentally and required for the beginning of the crushing, melting, total melting, and evaporation in unloading of a substance compressed by the shock wave are given in [1], and the intervals of the impact velocities for which the "spraying" or sputtering of the striker material is detected in microcraters by the strikers of different materials formed in soda-lime glass or fused quartz are presented in [2]. These data indicate that the dispersion of bodies is a widespread phenomenon in high-velocity impacts.

In this work, based on the hydrodynamic approach, we consider in a one-dimensional approximation the threshold velocities of impact for which the dispersion of the striker and target materials occurs and calculate the depth of a crater that is formed on impact of a body against the target surface.

Formulation of the Problem. Basic Relations on the Shock-Wave Front. Let us assume that the striker has the shape of a cylinder with a diameter exceeding the height and the target is a semibounded body. At the time of contact of the striker with the target surface, from the contact boundary there emerge two shock waves, one of which runs over the striker material and the other of which runs over the target material. We can consider these waves as being plane in the central part of the compression zone of the striker and target materials.

In what follows, we will denote the mechanical characteristics of the striker and target materials by indices 1 and 2 respectively and their values at atmospheric pressure additionally by the index 0.

Figure 1 shows schematically the penetration of the striker into the target when the shock wave has not yet reached the rear side of the striker; lateral expansions of the bodies are disregarded.

The laws of conservation of matter, momentum, and energy on the shock-wave front can be written in the form [3]

$$\rho_{i0}D_i = \rho_i\,(D_i - u_i)\,; \quad p_s = \rho_i D_i u_i\,; \quad \frac{p_s u_i}{\rho_{i0}D_i} = E_i - E_0 + \frac{u_i^2}{2}\,, \tag{1}$$

where $E_i = c_{vi}T_i$ (i = 1, 2).

The velocities u_1 and u_2 are related by the relation

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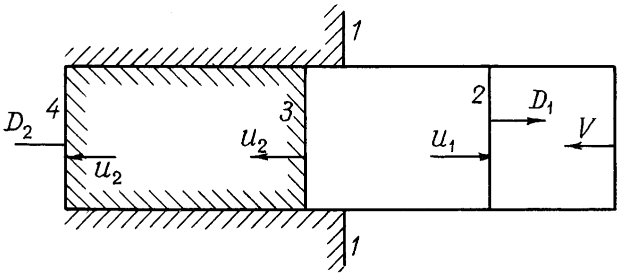

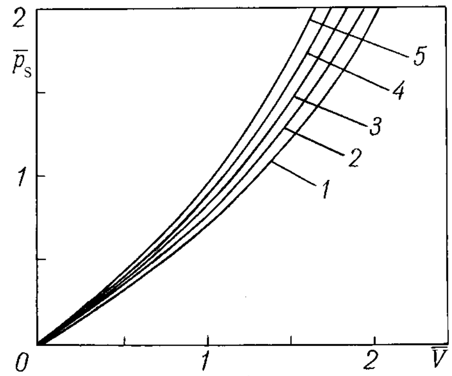

Fig. 1. Scheme of penetration of the striker into the target: 1) undisturbed surface of the target; 2) front of a reflected shock wave; 3) contact boundary; 4) front of a direct shock wave.

Fig. 2. Dimensionless pressure in the shock wave vs. ratio $\bar{V} = V/c_{10}$ for values of the exponent n from 1 to 5 (numbers at the curves).

$$u_1 + u_2 = V\,. \tag{2}$$

To close the system of equations (1)–(2), we must prescribe the equation of state of a substance behind the shock-wave front. For comparatively small amplitudes of pressure in the shock wave that are not considered here, the difference of the shock adiabat from the Poisson adiabat is slight, as is known [4]. For a number of metals we can use the simplest equation of an adiabat of the form

$$p = A\left[\left(\frac{\rho}{\rho_0}\right)^n - 1\right], \tag{3}$$

where A and n are constants related by the relation $An = \rho_0 C_0^2$ and $C_0 = (K/\rho_0)^{1/2}$ is the velocity of propagation of plastic waves for $p = 0$. From the data of [4], $A = 4.5\cdot10^{10}$ for iron, $2.5\cdot10^{10}$ for copper, and $2.03\cdot10^{10}$ N/m^2 for Duralumin; for metals, the exponent n can be set equal to 4.

The system of equations (1)–(3) yields the following relations:

$$\bar{V}^2 = \bar{p}_s(1-\theta_1)\left(1+\sqrt{\frac{\rho_{10}\theta_2}{\rho_{20}\theta_1}}\right)^2;$$

$$\bar{u}_1 = (\bar{p}_s\theta_1)^{1/2}, \quad \bar{u}_2 = \left(\frac{\rho_{10}}{\rho_{20}}\bar{p}_s\theta_2\right)^{1/2}; \quad \bar{D}_1 = \frac{\bar{u}_1}{\theta_1}, \quad \bar{D}_2 = \frac{\bar{u}_2}{\theta_2};$$

$$\theta_1 = 1-(1+n_1\bar{p}_s)^{-1/n_1}, \quad \theta_2 = 1-\left(1+\frac{K_1}{K_2}n_2\bar{p}_s\right)^{-1/n_2}; \quad \Delta T_1 = \frac{V^2}{2c_{v1}}\left(1+\sqrt{\frac{\rho_{10}}{\rho_{20}}\frac{\theta_2}{\theta_1}}\right)^{-2}, \quad \Delta T_2 = \frac{c_{v1}}{c_{v2}}\Delta T_1\,. \tag{4}$$

Thus, if the velocity of impact is known, relation (4) makes it possible to find all parameters of the medium in the shock wave.

In the case where the striker and the target are of the same material, the first equality of the system takes on the form

$$\bar{V}^2 = 4\bar{p}_s \left[1 - (1 + n\bar{p}_s)^{-1/n}\right]. \tag{5}$$

Figure 2 gives the curves of $\bar{p}_s$ as a function of $\bar{V}$ constructed from formula (5) for different values of n. These curves are universal in the region of applicability of the equation of state (3).

Calculation of the Parameters of Flow in the Zone of Unloading of the Striker Material. The first shock wave that moves over the striker material reaches its surface at the instant of time

$$t = t_0 = h_1/D_1\,, \quad h_1 = \frac{\rho_{10}}{\rho_1} h_0 = h_0\,(1 + n_1\bar{p}_s)^{-1/n_1}\,.$$

Simultaneously, the second shock wave goes deeper into the target to the distance

$$h_2 = D_2 t_0 = \frac{D_2}{D_1} h_1\,.$$

From the instant of time $t = t_0$ the unloading of the striker material begins. The unloading wave is a centered ordinary wave and is known to be described by the equations

$$V_1 = \frac{2}{n_1 + 1}\left(c_{1s} + \frac{x}{t}\right); \quad c_1 = \frac{2}{n_1 + 1} c_{1s} - \frac{n_1 - 1}{n_1 + 1}\frac{x}{t}\,, \tag{6}$$

where the origin of coordinates is brought into coincidence with the target surface, while the x axis is guided to the right, in the direction of motion of the substance.

The maximum velocity is attained for $p' = 0$ and is determined from the formula

$$V_{1m} = \frac{2c_{10}}{n_1 - 1}\left[\left(1 + \frac{p_s}{A_1}\right)^{\frac{n_1-1}{2n_1}} - 1\right]. \tag{7}$$

Downstream in the region of negative pressures the particles of the substance move by their own momentum; the material is extended. In the extension zone, the following equality is fulfilled:

$$V_1 = V_{1m} - \frac{2}{n_1 - 1}\,(c_{10} - c_1)\,.$$

Taking into account that $|p'| << A$ in this zone, we can rewrite the latter equality as

$$V_1 = V_{1m} - \frac{|p'|}{K_1}\,c_{10}\,.$$

If the tensile stress exceeds the tensile strength of the material, breaking or splitting off will occur at the corresponding site, i.e., a platelet of material moving with a certain velocity will split off of the body's surface. This splitting-off will be large-scale in nature with increase in the pressure p_s, i.e., the body will be dispersed.

The cross section in which the tensile stress attains the tensile strength of the material will be referred to as the "dispersion front." In what follows, the parameters of flow on the "dispersion front" will be denoted by asterisks. Then the condition of splitting-off or dispersion of the striker material will be written as

$$\rho^* V_1^{*2} > \sigma_1^*\,. \tag{8}$$

TABLE 1. Some Characteristics of Metals under Normal Conditions and Estimative Values of the Impact Velocity and the Pressure in the Shock Wave Required for Splitting Off in Unloading of a Substance to Atmospheric Pressure

Metal	ρ_0, g/cm^3	c_0, km/sec	K, N/m^2	σ^*, N/m^2	V^*, km/sec	P_s, N/m^2
Aluminum	2.73	5.1	$7.2\cdot10^{10}$	$2.65\cdot10^9$	1.83	$1.65\cdot10^{10}$
Iron	7.8	4.63	$16.7\cdot10^{10}$	$1.66\cdot10^9$	1.60	$1.83\cdot10^{10}$
Copper	8.93	3.95	$13.5\cdot10^{10}$	$1.60\cdot10^9$	0.93	$1.63\cdot10^{10}$
Lead	11.34	2.0	$4.5\cdot10^{10}$	$0.50\cdot10^9$	0.41	$0.52\cdot10^{10}$

Immediately ahead of the "dispersion front" the velocity is equal to

$$V_1^* = V_{1\mathrm{m}} = \frac{\sigma_1^*}{K_1} c_{10} , \tag{9}$$

and the "dispersion front" moves from right to left by the law

$$x^* (t) = -\left(c_{1\mathrm{s}} - \frac{n_1 + 1}{2} V_1^* \right) t = - M_1 c_{10} t ,$$

where $M_1 = \dfrac{n_1 + 1}{n_1 - 1} - \dfrac{2}{n_1 - 1}\dfrac{c_{1\mathrm{s}}}{c_{10}} + \dfrac{n_1 + 1}{2}\dfrac{\sigma_1^+}{K}$.

The "dispersion front" lags behind the unloading-wave front that moves by the law $x_\mathrm{f} = -c_\mathrm{s} t$; the gap between these two velocities decreases with increase in the impact velocity.

Having substituted (9) into (8), we can write the dispersion condition for the striker material as

$$p_\mathrm{s} > p_* = A_1 \left\{ \left[1 + \frac{n_1 - 1}{2} \frac{\sigma_1^*}{K_1} \left(1 + \sqrt{\frac{\rho_{10} K_1}{\rho_1^* \sigma_1^*}} \right) \right]^{\frac{2n_1}{n_1 - 1}} - 1 \right\} ,$$

where p_* is the threshold pressure in the shock wave for which the splitting-off begins.

Taking into account that the ratio $\sigma_1^*/K_1 << 1$, we can write

$$p_* = \sigma_1^* \left(1 + \sqrt{\frac{K_1}{\sigma_1^*}} \right). \tag{10}$$

If we now substitute $\bar{p}_* = p_*/K_1$ for $\bar{p}_\mathrm{s}$ in the first equality of system (4), we obtain

$$\bar{V}_*^2 = \bar{p}_* \left[1 - (1 + n_1 \bar{p}_*)^{-1/n_1} \right] \left[1 + \sqrt{ \left(\frac{\rho_{10}}{\rho_{20}} \frac{1 - \left(1 + n_2 \bar{p}_* \dfrac{K_1}{K_2} \right)^{-1/n_2}}{1 - (1 + n_1 \bar{p}_*)^{-1/n_1}} \right) } \right]^2 , \tag{11}$$

where $\bar{V}_* = V_*/c_{10}$.

Table 1 gives the characteristics of a number of metals under normal conditions and the estimative values of the impact velocity and the pressure in a shock wave required for splitting off in the case where the striker and the target are made of the same material. The values of σ^* are taken from [5]; the calculations

TABLE 2. Estimative Values of the Impact Velocity Required for Splitting Off in Unloading of a Substance to Atmospheric Pressure

Striker	Aluminum	Iron	Lead	Iron	Copper	Iron
Target	Iron	Aluminum	Iron	Lead	Iron	Copper
V_*, km/sec	1.31	2.66	0.34	1.84	1.63	1.60

were done by formulas (10) and (11). Table 2 gives the values of V_* in the case where the materials of the striker and the target are dissimilar.

Comparison of the data of Tables 1 and 2 shows that the quantity V_* largely depends on the ratio of the densities of the striker and target materials: the velocity V_* increases with decrease in the density of the target material.

For impact velocities higher than V_* the striker is dispersed; further increase in the impact velocity causes the striker material to melt and partially evaporate.

Calculation of the Depth of a Crater Formed on Impact of a Body against a Semiinfinite Target. Unloading of the target material begins when $t > t_1$. The unloading wave in the target material is also ordinarily centered and is described by the system of equations

$$V_2 = \frac{2}{n_2+1}\left(c_{s2} + \frac{x}{t}\right); \quad c_2 = \frac{2}{n_2+1} c_{s2} - \frac{n_2-1}{n_2+1}\frac{x}{t}, \quad t > t_1 . \tag{12}$$

At the contact boundary, the relations $p_1 = p_2$ and $V_1 = V_2$ are fulfilled and the equation of motion of the contact boundary has the form

$$\frac{dx}{dt} = \frac{2}{n_2+1}\left(c_{2s} + \frac{x}{t}\right). \tag{13}$$

Taking into account that, according to Eq. (13), the integral curve must pass through the point with coordinates $t = t_1$ and $x = -h_1$, we obtain

$$x_{\hat{e}} = t\left[\frac{2}{n_2-1} c_{2s} - \left(c_{1s} + \frac{2}{n_2-1} c_{2s}\right)\left(\frac{t_1}{t}\right)^{\frac{n_2-1}{n_2+1}}\right], \quad t > t_1 . \tag{14}$$

The striker material is fully dispersed at the instant of time $t = t_2$. To determine t_2, we note that for $t = t_2$ the coordinate x determined by the first equation of system (6) must be equal to the coordinate x_c determined by equality (14). From this condition we have

$$t_2 = t_1\left[\frac{n_2-1}{n_2+1}\left(\frac{c_{1s}}{c_{20}} + \frac{2}{n_2-1}\frac{c_{2s}}{c_{20}}\right)\right]^{\frac{n_2+1}{n_2-1}} . \tag{15}$$

From the instant of time $t = t_2$ the dispersion of the target material begins. At the same time, the shock wave followed by the unloading wave with velocity of motion $c_{2s} + u_2 > D_2$ continues to go deeper into the target. The unloading wave catches up with the shock wave at the instant of time $t = t_3$. The unloading wave moves over the striker material for a time $t_1' = h_1/(c_{1s} + u_2)$ and over the target material for a time $t_2' = (h_2 + h_3)/(c_{2s} + u_2)$; $t_1' + t_2' = t_3$.

On the other hand, in the time $t = t_3$ the shock wave reaches the depth $h_3 = D_2 t_3$ in the target. Thus, we have the following relation:

$$\frac{h_3}{D_2} = \frac{h_1}{c_{1s} + u_2} + \frac{h_2 + h_3}{c_{2s} + u_2} ,$$

which yields

$$h_3 = D_2 \frac{\dfrac{c_{2s} + u_2}{c_{1s} + u_2} + \dfrac{D_2}{D_1}}{c_{2s} + u_2 - D_2} h_1 .$$

For t_3 we obtain the following formula:

$$t_3 = h_1 \frac{\dfrac{c_{2s} + u_2}{c_{1s} + u_2} + \dfrac{D_2}{D_1}}{c_{2s} + u_2 - D_2} . \tag{16}$$

Taking into account that the velocity of sound c_2 in (12) is equal to

$$c_2 = c_{20} \left(1 + n_2 \frac{p}{K_2}\right)^{\frac{n_2 - 1}{2n_2}} ,$$

we can represent the analytical form of the pressure profile at the instant of time $t = t_3$ as

$$p'(x) = \frac{1}{n_2} \left[\left(\frac{2}{n_2 + 1} \frac{c_{2s}}{c_{20}} - \frac{n_2 - 1}{n_2 + 1} \frac{x}{c_{20} t_3} \right)^{\frac{2n_2}{n_2 - 1}} - 1 \right] .$$

When $t > t_3$ this profile decays; the shock wave is damped. It seems impossible to analytically describe this stage of the process. However, further dispersion of the target material is independent of the nature of decay of the shock wave.

The second wave reflected from the shock-wave front runs over the substance of the target (the substance is disturbed by the first unloading wave). In the zone between the shock-wave front and this reflected wave, the pressure decreases rapidly, while the dispersion of the material will continue only until the reflected wave intersects the "dispersion front" of the target material. We denote the instant of meeting of these two waves by t_4. The wave reflected from the shock-wave front is a characteristic of the flow and is determined by the equation

$$\frac{dx}{dt} = V_2 + c_2 .$$

On the line of conjugation of the reflected wave with the first unloading wave, the values of V_2 and c_2 are determined by equalities (12); hence the equation of the conjugation line can be written in the form

$$\frac{dx}{dt} = \frac{4}{n_2 + 1} c_{2s} + \frac{3 - n_2}{n_2 + 1} \frac{x}{t} . \tag{17}$$

The sought integral curve must pass though the point with coordinates (L, t_3), where

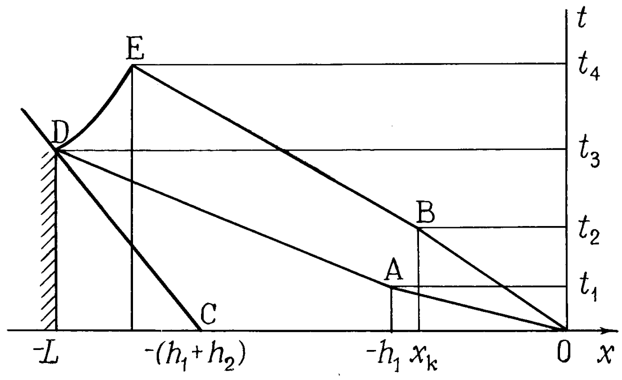

Fig. 3. Diagram of motion of the medium on the plane $x0t$: 0A = $-c_{1s}t$, unloading-wave front in the striker; 0B = $-M_1c_{10}t$, front of the "dispersion wave" of the striker; AD = $-c_{2s}t$, unloading-wave front in the target; BE = $-M_2c_{20}t$, front of the "dispersion wave" of the target; CD = $-D_2t$, shock-wave front in the target; DE, reflected-wave front; x, coordinate of the contact boundary.

$$L = h_1 + h_2 + h_3 = h_1 \frac{\left(1 + \frac{D_2}{D_1}\right)(c_{2s} + u_2) + \left[\frac{c_{2s} + u_2}{c_{1s} + u_2} - 1\right] D_2}{c_{2s} + u_2 - D_2} . \quad (18)$$

By integrating Eq. (17), we obtain

$$x = \frac{2}{n_2 - 1} c_{2s} t - \frac{n_2 + 1}{n_2 - 1} L \left(\frac{t}{t_3}\right)^{\frac{3-n_2}{n_2+1}} . \quad (19)$$

The "dispersion front" of the target material moves by the law

$$x^* (t) = -\left(c_{2s} - \frac{n_2 + 1}{2} u_{2m}\right) t = -M_2 c_{20} t , \quad (20)$$

where

$$M_2 = \frac{n_2 + 1}{n_2 - 1} - \frac{n_2 + 1}{2} \frac{\sigma_2^*}{K_2} - \frac{2}{n_2 - 1} \bar{c}_{2s} , \quad \bar{c}_{2s} = \frac{c_{2s}}{c_{20}} . \quad (21)$$

By equating the right-hand sides of equalities (19) and (20) we find t_4:

$$t_4 = t_3 \, (\bar{c}_{2s})^{(n_2+1)/2(n_2-1)} . \quad (22)$$

Figure 3 shows the diagram of motion in the unloading zones of the striker and target materials in the plane (x, t).

By the instant of time $t = t_4$ the pressure in the unloading zone of the material becomes lower than the limiting value p^* and the dispersion of the target material ceases. The depth H_1 to which the shock wave penetrates by this instant of time is equal to

TABLE 3. Values of the Dimensionless Parameters in the Unloading Zone of a Material (the striker and the target are of the same material)

$\overline{V}$	0.2	0.6	1.0	1.4	1.8	2.2	2.6	3.0
$\overline{p}_s$	0.113	0.415	0.820	1.328	1.934	2.643	3.448	4.351
θ	0.089	0.217	0.305	0.369	0.419	0.458	0.490	0.517
$\overline{c}_s$	1.150	1.443	1.725	1.995	2.254	2.505	2.746	2.980
$\overline{D}$	1.124	1.382	1.639	1.897	2.148	2.402	2.653	2.901
M	0.90	0.705	0.516	0.336	0.164	–0.004	–0.165	–0.321
$\overline{H}$	15.150	4.802	2.60	1.716	1.251	1.084	0.837	0.751
$\overline{H}_1$	17.20	6.95	4.79	3.86	3.31	2.95	2.70	2.51

$$H_1 = h_2 + h_3 + u_2 t_0 = h_0 \left[D_2 \frac{\dfrac{c_{2s}+u_2}{c_{1s}+u_2} + \dfrac{D_2}{D_1}}{c_{2s}+u_2-D_2} + \frac{D_2+u_2}{D_1} \right] (1 + n_1 \overline{p}_s)^{-1/n_1} . \quad (23)$$

Formula (23) has quite a definite physical meaning. If a plate is used as the target, for prescribed values of the impact velocity V and the striker length h_0 the quantity H is the critical thickness for which splitting-off will occur on the rear side of the plate.

The maximum depth of a crater formed on impact of a body against a semi-infinite surface is equal to the depth H to which the "dispersion front" penetrates by the instant of time t_4:

$$H = M_2 c_{20} (t_4 - t_2) + u_2 t_3 .$$

Substituting the values of t_2, t_3, and t_4 into this equality, we obtain

$$H = \left\{ \left[M_2 (\overline{c}_{2s})^{\frac{n_2+1}{n_2-1}} + \overline{u}_2 \right] \frac{\dfrac{(\overline{c}_{2s}+\overline{u}_2)}{(\overline{c}_{1s}+\overline{u}_2)} + \dfrac{\overline{D}_2}{\overline{D}_1}}{\overline{c}_{2s}+\overline{u}_2-\overline{D}_2} - \frac{M_2}{\overline{c}_{1s}} \left[\frac{n_2-1}{n_2+1} \left(\overline{c}_{1s} + \frac{2}{n_2-1} \overline{c}_{2s} \right)^{\frac{n_2+1}{n_2-1}} \right] \right\} h_0 (1 + n_1 \overline{p}_s)^{-1/n_1} , \quad (24)$$

where $\overline{u}_2 = u_2/c_{20}$, $\overline{c}_{1s} = c_{1s}/c_{10}$, $\overline{c}_{2s} = c_{2s}/c_{20}$, $\overline{D}_1 = D_1/c_{20}$, and $\overline{D}_2 = D_2/c_{20}$.

In the case where the striker and the target are made of one material, formulas (23) and (24) take on the form

$$\overline{H}_1 = \frac{H_1}{h_0} = \left[\frac{2D}{(c_s + u_2 - D)} + 1 + \frac{u_2}{D} \right] (1 + n\overline{p}_s)^{-1/n} , \quad (25)$$

$$\overline{H} = \frac{H}{h_0} = \left\{ \left[M (\overline{c}_s)^{\frac{n+1}{n-1}} + \overline{u}_2 \right] \frac{2}{\overline{c}_s + \overline{u}_2 - \overline{D}} - V (\overline{c}_s)^{\frac{2}{n-1}} \right\} (1 + n\overline{p}_s)^{-1/n} . \quad (26)$$

Table 3 gives the values of the dimensionless parameters of shock waves in the unloading zones of the materials calculated from formulas (18)–(21) and (24) and (25) for different values of the impact velocity. For pressures $p > 10^{11}$ N/m^2, the accuracy of the calculations is low since one can no longer disregard the entropy change in the shock wave. Nonetheless, the data of the table in the region of high pressures also convey correctly the dynamics of change in the medium’s parameters with increase in the impact velocity.

The table shows that, in high-velocity impact, the depth of the crater formed on the target surface decreases substantially with increase in the impact velocity. For impact velocities $V > 2.4c_0$, the depth of the crater becomes smaller than the linear dimensions of the striker.

This conclusion will hold qualitatively in consideration of a three-dimensional problem, too, since the lateral expansion in the unloading zone of the substance can only cause the depth of penetration of the dispersion front into the target to decrease.

Thus, for impact velocities $V > (12–13)$ km/sec, it is only the surface layers of the target that undergo failure, whereas the deep-seated layers where the shock waves penetrate are relaxed without failure to the material.

This phenomenon is found experimentally in [6] and bears the name "Leont'ev effect" in the foreign literature. The effect is that for impact velocities $V > 12$ km/sec a sharp increase in the radius and a decrease in the crater depth are observed; hollows are flattened out strongly. However, there are a number of publications (see, for example, [7]) in which the existence of the "Leont'ev effect" is doubted.

From the above investigations it is obvious that this effect has a real physical validity and is due to the fact that, as the impact velocity increases, the duration of the dispersion of the target material decreases; the failure cannot penetrate deep into the target, whereas the impact energy is mainly expended on the lateral scattering of the dispersion products of the striker and target materials.

The critical thickness H_1 of a sheet for which splitting-off can occur on the rear side also decreases substantially with increase in the impact velocity.

The calculations show that for the same impact velocity the values of H and H_1 depend mainly on the ratio $\chi = (\rho_{10}c_{10})/(\rho_{20}c_{20})$: the values of H and H_1 decrease with increase in χ.

We have considered above the process of dispersion of a substance in the unloading zone of the material in the coordinate system moving with a mass velocity u_2. As the calculations show, the relative velocity of particles u_r that are formed in dispersion of the substance is insignificant as compared to the impact velocity V and constitutes a value of the order of $0.1c_0$.

In a laboratory coordinate system, the dispersion products of the striker and target materials form a high-power flow that penetrates into the target with an absolute velocity equal to $(u_2 - u_\mathrm{r})$.

When $t > t_4$ the stresses in the compression zone of the target material are relaxed comparatively slowly under the head of this flow, and the process of dispersion ceases. With relaxation of the stresses, the bottom of the pit moves outward toward the particle flux and, like a piston, forces the mass of dispersed material out of the pit. This mass, expanding on the sides, destroys the pit walls; the upper walls are predominantly destroyed, whereas those at the bottom of the pit survive, forming a "shock funnel." This results in the formation of a crater whose typical shape is described, for example, in [7]: in the central part, we observe a hollow called the "shock funnel." The splitting-off zone that is a system of splitting-off shells adjacent to the shock funnel is located around it; the splitting-off shells resemble corollas of flowers.

For impact velocities $V > (12–13)$ km/sec, the depth of penetration of the dispersion into the target is smaller than the linear dimensions of the striker. The lateral separation of the dispersion products of the substance leads to a strong flattening-out of the hollows; the diameter of the craters formed is much larger than the depth.

Allowance for the lateral expansion of the substance in the shock wave cannot substantially alter the character of crater formation.

From our viewpoint, the above model of dispersion of solid bodies in high-velocity impacts can be applied to the phenomenon of the so-called superdeep-penetration effect. The essence of the latter is that, in loading of a metal target with a dense high-velocity flux of powder particles ($V \approx 1–3$ km/sec, $\rho \approx 0.5–5$ g/cm^3) a certain fraction of the particles (~1%) penetrates into the target to depths exceeding $(10^3–10^4)d$; the loss of particle mass attains 95–99% by the time of retardation. Channels formed by the particles in penetration into the target collapse; numerous changes in the direction of particle motion occur [9, 8].

This phenomenon can qualitatively be explained as follows. On impact of the flux of powder particles against a metal surface, the latter is bent in the shape of a spherical recess. Numerous long fractures whose direction deep into the target change occur from the recess surface in radial directions. The formation of such fractures is described, for example, in [2]. The powder particles that are incandescent in the shock wave and turn out to be just under such fractures are dispersed in the process of their unloading – the dispersion products are injected under high pressure into the channels of the fractures. The atoms and molecules of air and other gases contained in the pores inside the powder and, in the adsorbed state, on the particle surface are injected into the channels simultaneously with finely dispersed particles. At high temperatures these gases can enter into chemical reactions with the substances of the target and the powder. Upon unloading of the target material compressed by the shock wave, the channels of the fractures collapse; numerous carbonized powder particles up to 10^{-4}–10^{-5} cm or less in size turn out to be embedded in the target material. The lines along which the channels collapse look like the tract (trajectory) of the particles. Clearly, such a viewpoint needs experimental verification.

NOTATION

D_1 and D_2, velocity of the shock wave in the striker and target material; u_1 and u_2, mass velocity of the substance of the striker and the target behind the shock-wave front; ρ_{10} and ρ_{20}, initial density of the striker and target material behind the shock-wave front; ρ_1 and ρ_2, density of the striker and target material behind the shock-wave front; E_1 and E_2, internal energy of unit mass of the striker and the target; c_{v1} and c_{v2}, specific heat of the striker and the target at constant volume; V, impact velocity; p, pressure in the metal; ρ, metal density; ρ_0, metal density under normal conditions; n, adiabatic exponent; c_0, velocity of propagation of plastic waves in the metal for $p = 0$; K, compression modulus of the metal; $\overline{V} = V/c_0$, dimensionless impact velocity; p_s, pressure behind the shock-wave front; $\overline{p}_s = p_s/K_1$, dimensionless pressure in the shock wave; θ_1 and θ_2, relative compression of the striker and target material; K_1 and K_2, compression modulus of the striker and target material; $\overline{u}_1$ and $\overline{u}_2$, dimensionless mass velocity of flow in the striker and the target; T_1 and T_2, absolute temperature of the striker and the target behind the shock-wave front; n_1 and n_2, adiabatic exponent of the striker and target material; t, time; x, coordinate; h_0, initial thickness of the striker; h_1, thickness of the striker compressed by the shock wave; t_0, time of emergence of the shock wave on the rear surface of the striker; h_2, depth to which the shock wave penetrates into the target at the instant $t = t_0$; c_{1s} and c_{2s}, velocity of sound in the striker and target material behind the shock-wave front; V_1 and V_{1m}, velocity and maximum velocity of flow of the striker material in its unloading; V_1^*, flow velocity of the substance of the striker at the site of formation of a break; ρ_1^*, density of the target material at the site of its break; σ_1^*, splitting strength of the striker; $x^*(t)$, coordinate of the dispersion front; x_f, coordinate of the unloading front; x_c, coordinate of the contact boundary; p_*, threshold pressure in the shock wave for which splitting off occurs; V_*, threshold velocity of impact for which splitting off on the rear side of the striker begins; t_1, instant of time at which the unloading wave emerges at the target surface; V_2, flow velocity of the substance of the target in the unloading wave; c_2, velocity of sound in the unloading wave of the target material; p_1 and p_2, pressure in the striker and target material on the contact boundary; t_2, instant of time at which the striker is totally dispersed; t_1' and t_2', time for which the unloading wave moves over the striker and target material; $t_3 = t_1' + t_2'$, instant of time at which the unloading wave catches up with the shock wave in the target; h_3, depth at which the unloading wave catches up with the shock wave; p', pressure in the unloading wave; t_4, instant of time at which the process of dispersion of the target material ceases; H, funnel depth; H_1, critical thickness of the sheet for which splitting off occurs on its rear side; u_r, velocity of powder particles in a coordinate system tied to the compressed substance; d, diameter of powder particles.

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